Voltage Drop

Ed Renzi
# Voltage Drop (Single-Phase)

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<th>Formula:</th>
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<td>To Find Voltage Drop</td>
<td>[ \text{V.D.} = \frac{2 \times K \times L \times I}{\text{C.M.}} ]</td>
<td>C.M. = Circular Mill Area (Chapter 9, Table 8)</td>
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<td>To Find Voltage Drop Percentage</td>
<td>[ %\text{V.D.} = \frac{\text{V.D.} \times 100}{\text{Voltage}} ]</td>
<td>V.D. = Voltage Source x Percentage Allowed (Assume 3%)</td>
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<td>To Find Exact &quot;(K)&quot;</td>
<td>[ \text{R} \times \text{C.M.} ] [ \text{K} = \frac{\text{R} \times \text{C.M.}}{1000} ]</td>
<td>R = Resistance (Chapter 9, Table 8)</td>
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<td>Resistance: A Given Conductor (One Direction)</td>
<td>[ \text{Ohms D.C.} \times \text{L} ] [ \text{Ohms} = \frac{\text{Ohms D.C.} \times \text{L}}{1000} ]</td>
<td>Ohms = Value (Chapter 9, D.C. Table 8)</td>
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Length = Distance To Load (One Direction)
Voltage Drop Calculations

Series Circuit

In a series circuit, voltage (electro-motive force) pushes current (electrons) through a single path (conductor) around a circuit and back to its power source. A portion of this voltage is dropped off at each resistor and, by the time all of the voltage passes through all of the resistors, the total voltage is used up. This is consistent with Kirchoff’s Law, which states that “the sum of the voltages dropped at each resistor is equal to the source voltage.” Notice the series circuit below, all of the voltages used at all of the resistors add up to 24 volts. Also, all of the resistances add up to the total resistance of the circuit, This is because all of the resistance in a series circuit is accumulated along a single path. In this case 12 ohms.

![Series Circuit Diagram]

In a parallel circuit, all of the voltage at the source is available to each resistor, even though there are several paths for current to travel. Notice in the parallel circuit below; the entire 12 volts at the source is available at each resistor. Resistance in a parallel circuit is not accumulated, or added together along one path, like a series circuit. The reason why is that the voltage, or force, is the same everywhere in the circuit.

![Parallel Circuit Diagram]

Resistance (Good And Bad)

Up to now we have been talking about resistors as symbols in a circuit diagram. Most resistors, like light bulbs, toasters and electric heaters, in reality, are very useful devices. Even though these gizmos serve useful purposes by using electricity to do actual work, they aren’t perfect, and to some extent waste energy. A light bulb for instance gives off light but, at the same time gives off unneeded (wasted) heat.

Copper and aluminum conductors also are a little imperfect and contain some resistance. Chapter 9, Table 8 in the National Electrical Code gives us the actual resistance of conductors (per 1000 feet).
Notice the three columns on the right side of the Table. Copper Uncoated, Copper Coated and Aluminum. Copper Uncoated includes most conductors, like thermoplastic insulated and others. Copper Coated conductors includes rubber insulated (R-series) conductors which require an outer coating to keep the insulation from stretching. Aluminum conductors are listed on the last column.

Remember, the resistances given in Chapter 9, Table 8 are per 1000 feet. The resistance per 1000 feet of #14 stranded copper wire (quantity 7, i.e. strands) for instance is 3.14 ohms, while the resistance of #14 solid copper wire (quantity 1) is 3.07 ohms. As you can see, there is less resistance in a solid wire than in a stranded.

As you know, most conductors come in rolls of 500 feet, so the values in the Table will have to be adjusted for different lengths. Here’s a formula for finding resistance for conductors of varying lengths:

\[ R = \frac{\Omega \times \text{(Table 8)} \times \text{Length}}{1000} \]
Keep in mind that this formula calculates the resistance of one conductor only. To find the resistance of two conductors you’ll have to double the resistance, etc. For conductors in parallel, you must halve the resistance, (or divide by 2). This is because two conductors in parallel are taking the place of one conductor.

Conductor Resistance Problems...

(1) The resistance of 500 feet of #4/0 copper wire is ____ ohms?
(a) .1 Ω  (b) .528 Ω  (c) .0608 Ω  (d) .0304 Ω

(2) The resistance of parallel 500 kcMil THW conductors located 250 feet from a panel is nearest to ____ ohms.
(a) .00645 Ω  (b) .00581 Ω  (c) .00323 Ω  (d) .00290 Ω

Calculating Voltage Drop

The simplest way to calculate the voltage drop on conductors in a circuit you can use the formula...

\[ V.D. = I \times R \]

Check the following circuit...

In the above circuit the amps (I) equals 3. The resistance (R) for 350’ (175’ times two conductors) of #14 copper wire \((3.07 \times 350’)/1000 = 1.07\) ohms. The \( V.D. = I \times R \) formula should look like this...

\[ V.D. = 3 \times 1.07 \quad \text{or} \quad 3.21 \text{ volts dropped} \]
How about this one...

In this circuit there are 20 amps (I). The resistance (R) for 500’ (250’ times two conductors) of 
#12 copper wire (1.98 x 500’)/1000 = 0.99 ohms. The V.D. = I x R formula should look like 
this...

\[ V.D. = 20 \times 0.99 \quad \text{or} \quad 19.8 \text{ volts dropped} \]

**Voltage Drop Allowed**

The National Electrical Code has some recommendations as to how much voltage drop loss 
can be tolerated on conductors. Here they are....

For Branch Circuits...

210.19, FPN No. 4: Conductors for Branch Circuits (as defined in Article 100), sized to prevent a 
voltage drop exceeding 3 percent (at the farthest outlet of power, heating, and lighting loads, or 
combinations of such loads) and a maximum total voltage drop on both feeders and branch circuits (to 
the farthest outlet) not to exceed 5 percent, will provide reasonable efficiency of operation. See FPN No. 
2 of 215.2 (A)(3) for voltage drop on feeder conductors.

Between the power source (or service) and the farthest outlet of power, the Code allows a 
5% voltage drop loss. So if we have 240 volts at the service, we would be allowed a 12 volt loss 
(or a minimum of 228 volts) at the farthest outlet. But, only a 3% voltage drop loss would be 
allowed between the panel and the last outlet. That’s a maximum of 7.2 volts dropped on the 
branch circuit.
As far as Feeders are concerned...

**215.2 FPN No. 2:** Conductors for Feeders (as defined in Article 100), sized to prevent a voltage drop exceeding 3 percent (at the farthest outlet of power, heating, and lighting loads, or combinations of such loads) and a maximum total voltage drop on both feeders and branch circuits (to the farthest outlet) not to exceed 5 percent, will provide reasonable efficiency of operation.

As before, between the power source or service and the farthest outlet of power, the Code allows a 5% voltage drop loss. But, in this case only a 3% voltage drop loss would be allowed between the service and the panel. So if we had 240 volts at the service, we would still be allowed a 12 volt loss (or 228 volts at the last outlet). But, a maximum 3% voltage drop loss would be allowed between the service and the panel. That’s a maximum of 7.2 volts dropped on the feeder.

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**Voltage Drop Problems...**

(3) The required diameter of an electrical conductor is determined by _____.

(a) voltage  
(b) amperage  
(c) length  
(d) all of these

(4) The branch circuit allowable voltage drop of a 230 volt circuit is _____.

(a) \(2 \times R \times I\)  
(b) 230 x .03  
(c) 5%  
(d) 6.9 volts

(5) What does the National Electrical Code recommend for the voltage at the load in the above circuit ?

(a) 235.2  
(b) 232.8  
(c) 225.6  
(d) 228
Assume: On all branch circuits a 3% voltage drop is allowed unless we are given enough information as to what the actual voltage drop is.

Voltage Drop Formulas

Voltage drop can be lowered several ways. One way is to use a larger wire gauge because larger conductors have less resistance. Another way to lower resistance is to shorten the distance to the load. Also, increasing voltage will allow more volts to be dropped. Decreasing amps reduces the amount of current flowing on a circuit requiring a smaller wire size.

To calculate how much voltage is dropped on the conductors of a circuit we use the following formula...

\[ VD = \frac{2 \times K \times L \times I}{CM} \]

Your probably wondering what all those letters (variables) stand for...

“VD” of course stands for voltage drop.
“2” represents the two conductors in a circuit.
“K” is the constant or resistance factor (copper = 12.9, aluminum = 21.2).
“L” is the length of the conductor in one direction (we automatically multiply that by 2).
“I” stands for amps of the load.
“CM” is the circular mill (thickness) of the conductor from Chapter 9, Table 8.

Let’s put this formula to work in a problem...

A 240 volt, 25 amp heater is located 135 feet from a panel fed with two #10 THW conductors. Let’s find the voltage drop of the circuit.

Remember, we are trying to find the voltage drop of the circuit not the load. This is the wasted energy of the circuit not the energy used by the heater to do useful work, which is to keep us warm. Also, assume the conductor in the problem is copper, unless otherwise stated, (Article 110.5).

O.K., the formula for voltage drop is:

\[ VD = \frac{2 \times K \times L \times I}{CM} \]

The variables are:

\[ K = 12.9 \text{ (copper)} \]
\[ L = 135' \]
\[ I = 25 \text{ amps} \]
\[ CM = 10,380 \text{ Chapter 9, Table 8} \]

Plugging these values into the formula:

\[ VD = \frac{2 \times 12.9 \times 135' \times 25}{10,380} \]

\[ VD = 8.39 \]
Remember, we’re only allowed 3% voltage drop on our branch circuit. Here’s a formula for finding percentage of voltage drop.

\[
\%VD = \frac{VD}{\text{Voltage}} \times 100
\]

\[
\%VD = \frac{8.39}{240} \times 100
\]

\[
\%VD = 3.5\%
\]

As you can see the percentage of voltage drop exceeds the 3% allowed for branch circuits. In fact 3% of 240 volts is only 7.2 volts, so we are 1.19 volts over the limit. We can solve this dilemma by choosing a new (larger conductor). Here’s the formula for finding a new conductor...

\[
CM = \frac{2 \times K \times L \times I}{VD}
\]

Now, let’s remove the #10 THW conductors feeding the heater and find some new ones based on a voltage drop of 3% or 7.2 volts:

The variables are:

\[
CM = \frac{2 \times K \times L \times I}{VD}
\]

\[
K = 12.9 \text{ (copper)}
\]

\[
L = 135'
\]

\[
I = 25 \text{ amps}
\]

\[
VD = 7.2 \left(240 \times .03\right)
\]

Plugging these values into the formula:

\[
CM = \frac{2 \times 12.9 \times 135' \times 25}{7.2}
\]

\[
CM = 12.094
\]

If we use #8 copper conductors (Chapter 9, Table 8) we would have a total of 16,510 circular mills to work with. This would meet the requirement of at least 12,094 required by the formula.
(6) The voltage drop on two #12 THW solid copper conductors 150 feet long connecting a 1/2 horsepower (9.8 amp), single-phase motor to a 115 volt source would be ____ volts.

(a) 3.45  (c) 5.8  
(b) 5  (d) 7.2

(7) The size wire is needed for a 115 volt, 30 amp load, located 120' from its voltage source is?

(a) #4  (c) #8  
(b) #6  (d) #10

(8) The copper conductor size for the circuit diagram above is ______.

(a) #4  (c) #8  
(b) #6  (d) #10

(9) What is the circular mills with a voltage drop of 3% in the above diagram?

(a) 21,000-25,000  (c) 221,000-230,000  
(b) 200,000-220,000  (d) 231,000-250,000

(10) What size conductor is required for question (9)?

(a) #250 kcMil  (c) #3/0  
(b) #4/0  (d) #2/0

(11) An 80' deep well is located 160' from the house panel. in the well is a 1/2 horsepower (9.8 amp), 115 volt pump. What copper wire size is required?

(a) #10  (c) #6  
(b) #8  (d) #4
Finding Amps And Length Using The Voltage Drop Formulas...

Here are some other related formulas:

This one determines conductor length... \[ L = \frac{CM \times VD}{2 \times K \times I} \]

This one determines conductor amps... \[ I = \frac{CM \times VD}{2 \times K \times L} \]

Let's use these formulas in some problems...

A short circuit has developed in a #14 copper wire. All 6 volts applied to the circuit are dropped and an amp meter reads 2 amps. Can you find the length of the conductor to the short?

Let's apply the formula for conductor length...

\[
CM = 4,110 \text{ (}#14\text{)} \\
VD = 6 \text{ (100% voltage drop)} \\
K = 12.9 \text{ (copper)} \\
I = 2 \text{ amps}
\]

\[
L = \frac{CM \times VD}{2 \times K \times I} = \frac{4,110 \times 6}{2 \times 12.9 \times 2} = 477.9 \text{ feet}
\]

Good luck tracking that short down! How about another one...

Can you find the amps at the load of a 120 volt circuit, 143 feet long, using #12 THW aluminum conductors?

Let's apply the formula for amps at the load:

\[
CM = 6,530 \text{ (}#12\text{)} \\
VD = 3.6 \text{ (120 x .03)} \\
K = 21.2 \text{ (aluminum)} \\
L = 143'
\]

\[
I = \frac{CM \times VD}{2 \times K \times L} = \frac{6,530 \times 3.6}{2 \times 21.2 \times 143} = 3.88 \text{ amps}
\]

As you can see voltage drop can pay a high toll!

A More Precise “K”

You might be wondering about “K” and where it came from? Well, “K” is based on the resistance of a circular mill of a conductor (copper or aluminum) by the foot. You can find it by this formula...

\[
K = \frac{R \times CM}{1000}
\]

Let's find ‘K’ for a #14 stranded copper conductor...

\[
R = 3.14 \text{ (#14 stranded copper uncoated)} \\
CM = 4110 \text{ (#14 AWG)}
\]

\[
K = \frac{3.14 \times 4110}{1000} = 12.9054
\]

If we guessed 12.9 we would have been pretty close.
Voltage Drop Sample Problem...

There are two #1/0 THW aluminum wires feeding a 100 amp panel at a distance of 200 feet. What size copper wire could be used in order to have an equal voltage drop to the existing aluminum wires?

Solution:

To find the voltage drop of the #1/0 aluminum conductor:

\[
\text{V.D. } = \frac{2 \times K \times L \times I}{\text{C.M.}}
\]

\[
K_{(al)} = 21.2 \\
L = 200' \\
I = 100 \\
\text{C.M.} = 105,600
\]

\[
\text{V.D. } = \frac{2 \times 21.2 \times 200 \times 100}{105,600} \\
\text{V.D. } = 8.03 \text{ (volts dropped)}
\]

To find circular mills of equal copper wire:

\[
\text{C.M. } = \frac{2 \times K \times L \times I}{\text{V.D.}}
\]

\[
K_{(cu)} = 12.9 \\
L = 200' \\
I = 100 \\
\text{V.D.} = 8.03
\]

\[
\text{C.M. } = \frac{2 \times 12.9 \times 200 \times 100}{8.03} \\
\text{C.M. } = 64,259 \text{ (Chapter 9, Table 8) #2 copper (66,360 C.M.)}
\]

Replace the 1/0 aluminum wires with #2 copper wires.
More Voltage Drop Problems...

(12) A load at 115 volts located 250 feet from a panel is fed with a #14 conductor. The amps at the load is approximately ____.

(a) 8.2 amps  
(b) 3.5 amps  
(c) 2.2 amps  
(d) 1.7 amps

(13) A #12 two conductor cable carrying 115 volts from the source is buried underground, it feeds a 16 amp motor. A reading shows 110.3 volts at 16 amps at the motor. The length of the conductor is approximately ____ feet.

(a) 35’  
(b) 48’  
(c) 74’  
(d) 96’

(14) A 45 amp load at 120 volts is located 400 feet from a panel. What size copper wire will be required?

(a) #1/0  
(b) #2/0  
(c) #3/0  
(d) #4/0

(15) A 3/4 horsepower pool pump (13.8 amps), rated 115 volts, is located 124 feet from the panel. What size copper wire is recommended?

(a) #10  
(b) #8  
(c) #6  
(d) #4
Voltage Drop Answers

(1) B (3%)

(2) D

(3) D (240v x .03 = 12) (240v - 12v = 228v)

(4) D (R = \frac{.0608 \times 500}{1000})

(5) A (CM = 2 \times 12.9 \times 120' \times 30) \frac{3.45}{3.45}

(6) D (CM = 2 \times 12.9 \times 180' \times 11) \frac{5}{5}

(7) D (CM = 2 \times 12.9 \times 350' \times 180) \frac{6.6}{6.6}

(8) A

(9) B (Amps = \frac{4110 \times 3.45}{2 \times 12.9 \times 250})

(10) C (Length = \frac{6530 \times 4.7}{2 \times 12.9 \times 16})

(11) B (CM = 2 \times 12.9 \times 400' \times 45) \frac{3.6}{3.6}

(12) C (CM = 2 \times 12.9 \times 240' \times 9.8) \frac{3.45}{3.45}

(13) C (CM = 2 \times 12.9 \times 124' \times 13.8) \frac{3.45}{3.45}

(14) C (R = \frac{.0129 \times 250}{1000})
## Voltage Drop (New Method)

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<td><strong>To Find Circular Mills Of Conductor</strong> (@75°C)</td>
<td>R = [rac{\text{V.D.} \times 1000}{2 \times L \times I}]</td>
<td>R = Resistance Value (Chapter 9, Table 8)</td>
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<td><strong>To Find Amps</strong> (@75°C)</td>
<td>I = [rac{\text{V.D.} \times 1000}{2 \times R \times L}]</td>
<td>I = Load Ampacity (Continuous Load Does Not Apply)</td>
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<tr>
<td><strong>To Find Length</strong> (@75°C)</td>
<td>L = [rac{\text{V.D.} \times 1000}{2 \times R \times I}]</td>
<td>L = Distance From Source To Load (One Direction)</td>
</tr>
<tr>
<td><strong>Temperature Change Formula</strong> (Not @75°C)</td>
<td>R2 = R1 [1 + a (T2 - 75)]</td>
<td>R1 = Temperature Of Conductor At 75°C</td>
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<td>T2 = New Temperature</td>
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# Voltage Drop (Three-Phase)

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<td>(Continuous Load Does Not Apply)</td>
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<td>Length = Distance From Source To Load</td>
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<td></td>
<td>(One Direction)</td>
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<td></td>
<td>Aluminum = 21.2</td>
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<td>To Find Exact &quot;K&quot;</td>
<td>( K = \frac{\text{R} \times \text{C.M.}}{1000} )</td>
<td>R = Resistance (Chapter 9, Table 8)</td>
</tr>
<tr>
<td>To Adjust &quot;R&quot; For Temperature Change</td>
<td>( R_2 = R_1 \left[1 + a \left(T_2 - 75\right)\right] )</td>
<td>a = alpha .00323 copper</td>
</tr>
<tr>
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<td></td>
<td>.00330 aluminum</td>
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